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OPTIMAL YIELD LEVEL OF BILINEAR SEISMIC ISOLATION DEVICES

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SUMMARY

The yield level of an insulator is one of the important parameters which are related to responses and absorbing energy under seismic input energy in isolated structures. The purpose of this paper is to determine the optimal ratios of yield force of the isolator (Q_y) to the total weight of the structures (W). To obtain the optimal ratio, 1044 two-degree-of-freedom isolated bridge models, which have bilinear isolators, were selected. These 2-DOF isolated bridge models with superstructure isolation can consider pier flexibility and various parameters of the isolator. Two formulas for determining the optimal yield ratio are proposed and compared with the previous researches. RAE (the ratio of absorbed energy by the isolator to the total input energy) is related directly to structural responses, and Optimal Yield Ratio (OYR), defined as a yield ratio at maximum RAE, can be obtained from the relationship between RAE and Q_y/W. Here, we found that RAE is a reliable factor to evaluate OYR, and it is proportional to earthquake amplitudes under the same kinds of earthquake loadings. Using the proposed formulas, OYR is determined and the optimal yield force of the isolator can be obtained easily and reliably at a seismic isolation design stage. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: Optimal yield ratio of isolator; two-step seismic isolation design; absorbed energy

1. INTRODUCTION

It is in recent years that base isolation has become a practical strategy for an earthquake-resistant design. This technology offers a reliable and cost-effective strategy for mitigating seismic damage to structures.[1] To realize a more reliable and effective seismic isolation design, an improved design method is required. In a seismic isolation design, parameters of the isolator are very important and these parameters control overall behaviors of isolated structures. Thus, more reliable parameters of the isolator are required at a preliminary seismic isolation design stage. Especially, one of the most important parameters is Q_y/W (the ratio of the yield force of the isolator Q_y and the total weight of structure W) and it is largely related to structural responses and the absorbing energy of isolators under severe earthquake loadings.

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In this paper, OYR (optimal ratio of yield force of the isolator to total weight of structures) is investigated and formulas for determining OYR will be proposed for the super-structure isolation highway bridges with bilinear isolators. Here, OYR is defined as the value of Q_y/W at maximum RAE (the ratio of absorbed energy by the isolator to total input seismic energy).

Skinner discussed the optimal ratio of yield force of the isolator to total weight of structures (Q_y/W) for a minimum base shear under an EI Centro NS 1940 earthquake, scaled to the given elastic and plastic period of isolators. Here, he described that the optimal yield level, (Q_y/W)opt, for minimum base shear scales directly with the amplitude scaling of the earthquake. Thus if $Q_y = 0{\cdot}05W$ is optimal for EI Centro, $Q_y = 0{\cdot}10W$ will be optimal for two times the El Centro motion if all other parameters are held fixed.[2] In AASHTO specification for seismic isolation design, there is no detailed guideline for the yield force of the isolator according to each earthquake level. In Dynamic Isolation Systems Inc. (DIS) seismic isolation design procedure, the ratio of the characteristic strength values Q_d and structural weight W is used as 0·03, 0·05, 0·07, and 0·10. But there is no mention of any of the levels of earthquakes.

In this paper, using the energy concept, OYR will be examined and obtained for all possible bilinear models up to now under various earthquake loadings and levels.

This research will discuss only regular highway bridges having superstructure isolation not including a skewed, an arched and a long bridge. This regular bridge can be modeled as 2-DOF which consists of mass and spring. The material model of piers is modelled as an elastic shear spring and that of isolators is modelled as a bilinear shear spring. The effects of abutments are not considered. There are two kinds of seismic isolation devices; linear type and bilinear type. But in this paper, only the bilinear-type isolator will be discussed since to date, a large number of seismic isolation devices can be represented by the bilinear model.

The El Centro NS 1940 earthquake is selected as an external horizontal load and scaled to be analysed under a various earthquake amplitude. A systematic study is undertaken to obtain more reliable results for a total of 1044 2-DOF isolated bridge models according to elastic, plastic period and Q_y/W. To represent these models mathematically, an absolute energy equation of motion is introduced since the energy concept is a useful method to explain the behavior of isolated structures. To solve this energy equation of motion, the step by step Newmark numerical method is used, and structural responses and an amount of absorbed energy are obtained under the scaled earthquake loadings for all models.

The OYR obtained is very reliable values for yield force of the isolator since the OYR come from RAE, it is a very acceptable factor (see the results of this study) for estimating seismic resistance. Two formulas for determining OYR are proposed from the relationship between RAE and Q_y/W. These proposed formulas are validated for two different kinds of earthquake loadings (Taft 1952 and Kobe 1995).

2. ABSOLUTE ENERGY EQUATION OF MOTION

2.1. Selected earthquake loadings

Figure 1 shows the selected earthquake loading (El Centro NS 1940) for 10 sec. The time step is 0·02 sec. This earthquake include predominant periods ranging from 0·5 to 1·0 sec. The maximum earthquake acceleration is $0{\cdot}35g$ ($g = 980$ cm/sec^2, gravity acceleration) and the amplitude will be

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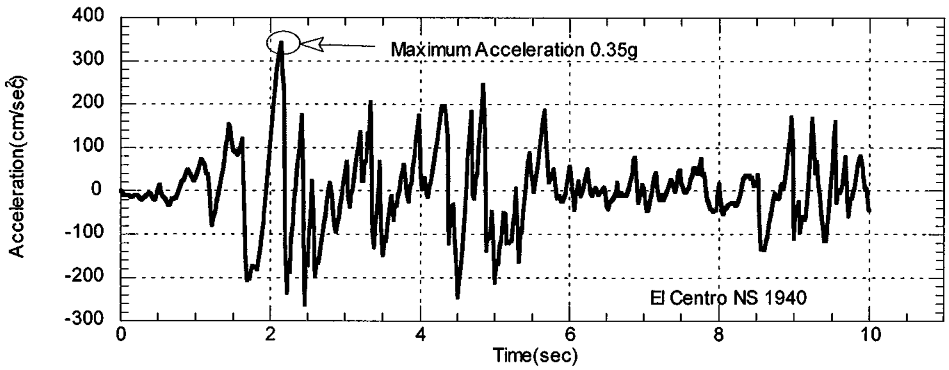

Figure 1. Earthquake loadings

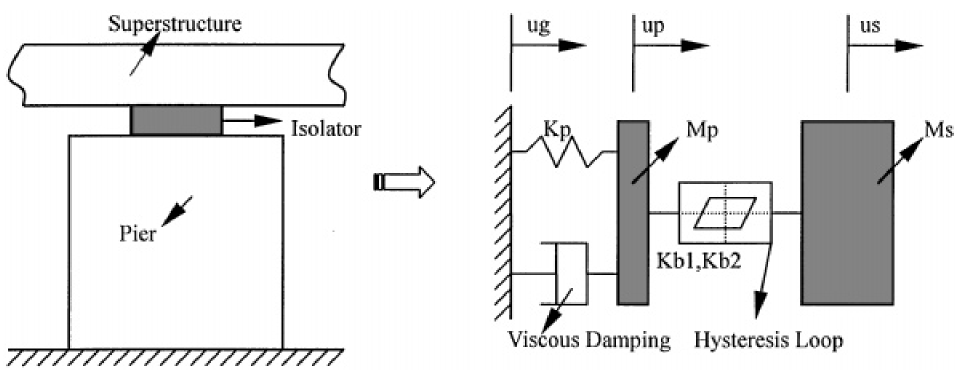

Figure 2. Selected 2-DOF isolated bridge model with a bilinear isolator

scaled to seven levels using amplitude scaling factors, $P_a = 0{\cdot}5, 1{\cdot}0, 1{\cdot}5, 2{\cdot}0, 2{\cdot}5, 3{\cdot}0, 3{\cdot}5$. The period scaling factor P_p is constant as 1·0.

$$\ddot{u}_g(t) = P_a \ddot{u}_{ELC}(t/P_p) \tag{1}$$

Equation (1) shows scaled earthquakes by P_a, P_p and $\ddot{u}_{ELC}(t)$ which are the accelerations for the earthquake, El Centro NS 1940.

2.2. Selected 2-DOF isolated bridge models

Figure 2 shows the selected 2-DOF isolated bridge model. The pier is modelled as a linear shear spring and the isolator is modelled as a bilinear shear spring. In Figure 2, 'u_g' is ground acceleration, 'u_p' is displacements of piers, 'u_s' is displacements of superstructures, 'K_p' is stiffness of piers, 'K_{b1}' is elastic stiffness of isolators, 'K_{b2}' is plastic stiffness of isolators, 'M_p' (=20 kg) is mass of piers and 'M_s' (=1000 kg) is mass of superstructures. We assume that the structural damping ratio is 0·02, superstructures are straight and the ratio of the mass of piers to that of the superstructures is 0·02, for selected models. For the usual case, when the pier mass is much smaller

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Table I. Earthquake levels and parameters of isolated bridge models

Parameter	Symbol	Value	Unit
Maximum acceleration of seismic loading	MA	0·175g, 0·35g, 0·525g, 0·7g, 0·875g, 1·05g, 1·225g	cm/sec^2
First period of unisolated model	T_{O1}	0·25, 0·50, 0·75	sec
Elastic period of the isolator	T_{b1}	0·3, 0·6, 0·9	sec
Plastic period of the isolator	T_{b2}	1·5, 3·0, 4·5, 6·0	sec
Yield ratio of the isolator	Q_y/W	0·02–0·3 (0·01 interval)	

than the superstructure mass, the pier mass may be neglected when evaluating approximate seismic responses of the superstructure. In this case the spring forces of the pier and isolator component may be combined statically to give the composite spring force for the support. Moreover, the pier mass makes no significant contribution to the model.[2]

Table I shows the selected earthquake levels and parameters of the isolated bridge models. 1044 models are selected according to the natural period of unisolated models, elastic period, plastic period and yield force for isolators. These models can represent highway bridge structures with a bilinear-type isolator. Seven earthquake load levels, three first natural periods of unisolated structures, three elastic period of the isolator, four plastic periods of the isolator and 29 yield ratio of the isolator are all selected for analysis as possible parameters of bilinear isolators up to now.

For typical structures with bilinear isolation involving energy dissipation through hysteresis of lead or steel, the parameter values tend to represent low, medium and high values. Responses for some other limiting cases may be evaluated readily. For example, $Q_y/W = 0$ gives a linear isolator, and T01 $= 0$ sec gives a rigid structure with seismic responses simply related to the maximum responses of these bilinear bridge models. Designs using other types of bilinear isolation systems may have parameter values well outside these ranges.[2]

2.3. Absolute energy equations of motions

Equation (2) shows the 2-DOF 'absolute' energy equation to represent isolated bridge models. The use of an 'absolute' energy equation rather than a 'relative' energy equation has the advantage that the physical energy input is reflected.[3] In equation (2), $[M]$ is mass matrix, $\{\dot{u}_a^t\}$ is absolute velocity vector, $[C]$ is viscous damping matrix, $\{F(u_r^t)\}$ is restoring force vector, $\{u_r^t\}$ is relative displacement of the masses with respect to the ground, $\{\dot{u}_g^t\}$ is earthquake ground velocity vector, t is earthquake complete time and $\dot{u}_a^t = \dot{u}_r^t + \dot{u}_g^t$.

The 'absolute' energy equation for a multi-degree of freedom subjected to an earthquake ground motion has been derived as follows:

$$\frac{1}{2}[M]\{\dot{u}_a^t\}^{\mathrm{T}}\{\dot{u}_a^t\} + \int_0^t \{\dot{u}_r^t\}^{\mathrm{T}}[C]\{\dot{u}_r^t\}\,\mathrm{d}t + \int_0^t \{F(u_r^t)\}\{\dot{u}_r^t\}\,\mathrm{d}t = \int_0^t [M]\{\ddot{u}_a^t\}\{\dot{u}_g^t\}\,\mathrm{d}t \tag{2}$$

In equation (2), the right-hand side express the total seismic input energy, most of the input energy will be absorbed by the hysteresis loop of the isolator in the left-hand side of equation (2). The first term of equation (2) is kinetic energy and it will disappear when the earthquake is completed. The second term of equation (2) is force by a viscous damping and it assumed as a 0·02 damping ratio.

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The third term represent hysteresis absorbed energy by the isolator. Equations (3) and (4) show Total Input Energy (TIE) and hysteretic Absorbed Energy by the Isolator (AEI).

$$\mathrm{TIE} = \int_0^t [M]\{\ddot{u}_{\mathrm{a}}^t\}\{\dot{u}_{\mathrm{g}}^t\}\,\mathrm{d}t \tag{3}$$

$$\mathrm{AEI} = \int_0^t F(u_{\mathrm{r}}^t)\{\dot{u}_{\mathrm{r}}^t\}\,\mathrm{d}t \tag{4}$$

Here, we can define the degree of energy absorption to the external seismic loadings for isolated structures as equation (5) since most of the external energy is absorbed by the isolator.

$$\mathrm{RAE} = \frac{\mathrm{AEI}}{\mathrm{TIE}} \tag{5}$$

The amount of total input seismic energy is followed by the first natural period of structures and total mass, regardless of the distribution of mass and stiffness. The input energy can be absorbed by the hysteretic loop mainly in isolated structures with the hysteretic damping isolator. Therefore, the seismic resistance may be evaluated by the amount of absorbed energy to the total seismic input energy. This RAE is a very important factor to control structural responses for isolated structures under seismic loadings and it can evaluate the degree of earthquake resistance.

3. EFFECTS OF RAE TO STRUCTURAL RESPONSES

Figures 3–5 show the effects of RAE to various structural responses and the variability in structural responses. Here, it will be shown for only two earthquake levels (0·175g and 1·225g) since a similar inclination is shown for other earthquake levels. The characters 'S' and 'G' mean 'Scattered Values' and 'Gathered Values' of responses with respect to RAE. These imply the variability in the structural responses. Generally, the values of structural responses approach the low values as the RAE increases. Absolute Maximum Displacements (AMD (cm)) Absolute Maximum Accelerations (AMA (cm/sec^2)) and AMSW is the ratio of absolute maximum shear forces to the total weight of the structures. All structural responses have absolute maximum values since only absolute maximum values are meaningful at a real design stage. The shear forces are expressed as the ratio of Absolute Maximum Shear forces (AMS) at piers, and total weight of structures (W), AMSW, in Figure 3(a).

To investigate the effects of RAE to the structural responses shear forces, displacements and accelerations are examined for all the selected models (1044 models) under each earthquake level (seven earthquake levels). Displacements and accelerations are obtained at superstructures and shear forces are obtained at the bottom of piers as absolute maximum values.

Here, three important facts are found, first, all structural responses are inversely proportional to the RAE, second, these responses in the range of high RAE have values gathered (steady response values) regardless of model kinds, and finally, values of responses are more proportional under small earthquake levels than large earthquake levels to the RAE. From these results, we can introduce the maximum RAE as a design factor to evaluate seismic resistance based on the results shown in Figures 3–5. Using these RAE, the optimal yield ratio will be obtained.

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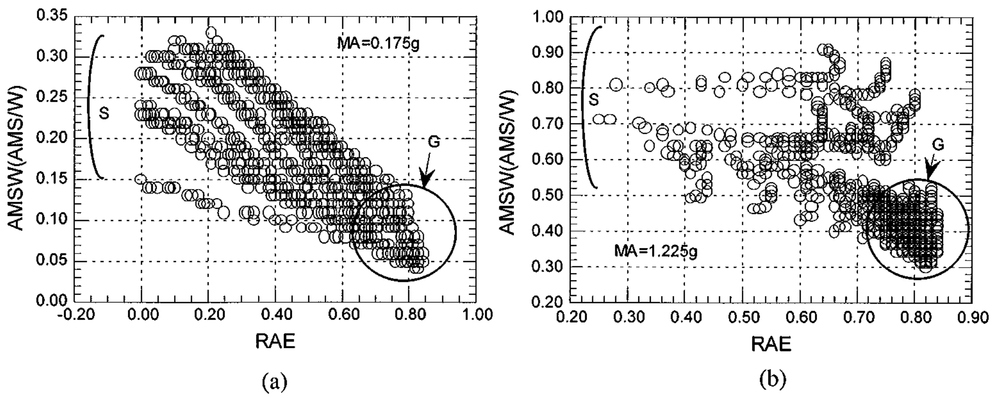

Figure 3. Absolute Maximum Shear Forces Divided by Weights (AMSW) and RAE: (a) AMSW and RAE under 0·175g; (b) AMSW and RAE under 1·225g

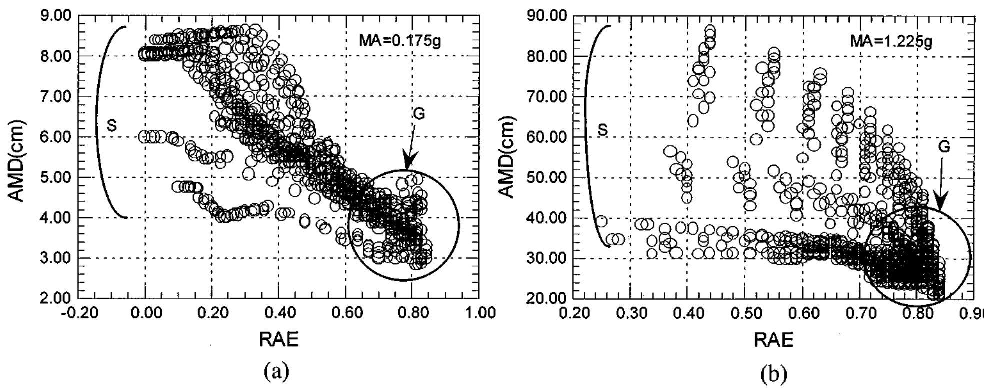

Figure 4. Absolute Maximum Displacements (AMD) and RAE: (a) AMD and RAE under 0·175g; (b) AMD and RAE under 1·225g

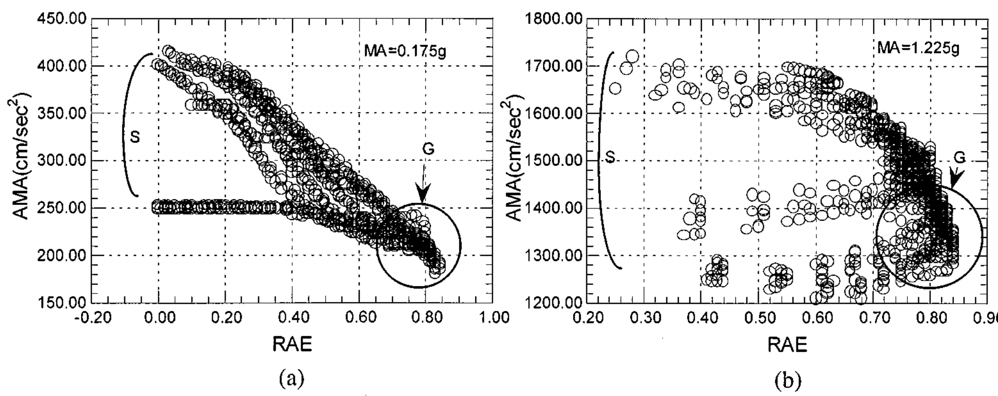

Figure 5. Absolute Maximum Accelerations (AMA) and RAE: (a) AMA and RAE under 0·175g; (b) AMA and RAE under 1·225g

3.1. Shear forces at piers

Absolute maximum shear forces designated as AMSW in this paper are related to structural member size and failure modes directly. Thus, this is one of the most important factors to evaluate the earthquake resistance. In Figure 3(a), AMSW is shown to have a more proportional inclination than Figure 3(b). Both of these two cases have scattered values at low RAE but gathered values at high RAE. For the same earthquake level, AMSW at low RAE is about 3 times larger than that at high RAE. This fact means we must choose an isolator with high RAE under a given earthquake design level to improve earthquake resistance.

3.2. Dispalcements at superstructures

Absolute maximum displacements designated as AMD are related to the serviceability of structures under an usual condition. Especially, in the case of bridge structures, the big gap between girders and abutments due to seismic isolation design displacements become big problems. To improve serviceability for usual conditions, if all possible, small seismic isolation design displacements must be taken. In Figure 4(a), AMD is shown to be a more proportional inclination than in Figure 4(b). Both of these two cases have scattered values at low RAE but gathered values at high RAE. For the same earthquake level AMD at low RAE is about 2 times larger than that at high RAE. This fact means we must choose an isolator with high RAE under a given earthquake design level to improve serviceability of structures.

3.3. Accelerations at superstructures

Absolute maximum accelerations denoted as AMA are related to shear forces of structural members and serviceability of seond structures. In Figure 5(a), AMA is shown to have a more proportional inclination than in Figure 5(b). Both of these two cases have scattered values at low RAE but gathered values at high RAE. For the same earthquake level AMA at low RAE is about 2 times larger than that at high RAE. Thus, as possible, we must choose an isolator which can reduce accelerations more than ever.

4. EFFECTS OF EARTHQUAKE AMPLITUDE TO RAE

Figure 6 shows the relationship between shear force and a displacement of an isolator, and a pier for two different kinds of MA, to investigate effects of MA to RAE for a given isolated model representatively. Table II shows analysis results (TIE, AEI, and RAE) for the given model. The given model which is one of the selected models in Table I has constant parameters ($T_{01} =$ 0·25 sec, $T_{b1} = 0{\cdot}3$ sec, $T_{b2} = 6{\cdot}0$ sec, and $Q_y/W = 0{\cdot}02$). In this analysis, we can see that RAE is changing with MA for a given model. As mentioned above, RAE is related to structural responses deeply and the given model with low RAE ($=0{\cdot}41$ under $1{\cdot}225g$) can receive larger damages at a pier than a different model with high RAE ($>0{\cdot}41$) under the same MA.

From this result, we can see that RAE is varying with MA and, on the contrary, it implys that RAE can be increased by changing the parameters of the isolator. Especially, the yield ratio of the isolators is the most important factor which controls damping ratios, displacements and shear

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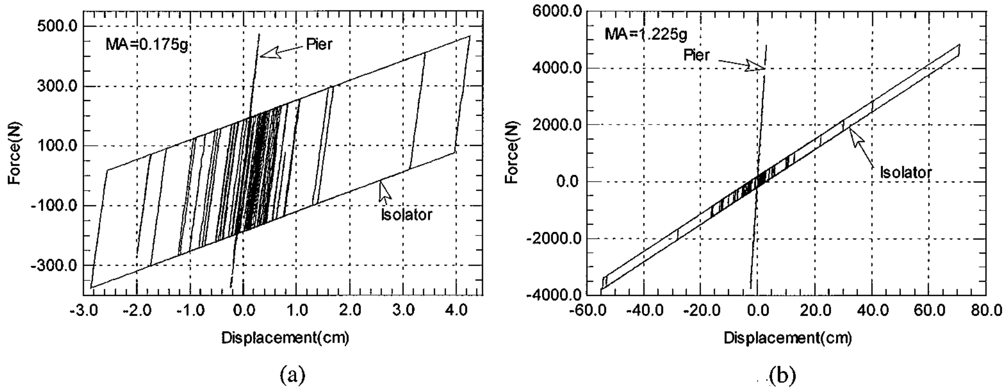

Figure 6. Relationship between shear forces and displacements of the example model: (a) Force and Displacement under 0·175g; (b) Force and Displacement under 1·225g

Table II. Analysis results for example model

MA	TIE (N cm)	AEI (N cm)	RAE
0·175g	10 885	9043	0·83
1·225g	444 028	278 496	0·41

forces. Here, OYR needs to be determined according to MA. If we can obtain OYR for an earthquake level, a more reliable and safe seismic isolation design can be accomplished.

In this paper, RAE will be investigated for a total of 7308 cases and OYR will be obtained for 36 isolated bridge models which can represent all bilinear isolators up to now.

5. OPTIMAL YIELD LEVEL OF SEISMIC ISOLATION DEVICES

5.1. Maximum RAE according to several earthquake levels

Figure 7 shows the relationship between RAE and Q_y/W to find maximum RAE at each of the levels of earthquakes. The analysis is conducted for seven earthquake levels but Figure 7 shows 4 earthquake levels (0·175g, 0·525g, 0·875g, and 1·225g). In Figure 7, ML represents the maximum line which is connected with the maximum RAE. Here, we can see Q_y/W at a maximum RAE of each model (OYR) has very similar values regardless of parameters of the isolator (Tbl and Tb2) as shown in Table III (if a given earthquake level is the same). Table III shows OYR for 36 basic models which can represent the bilinear isolator up to now under 7 earthquake levels. $(\mathrm{OYR})_{\mathrm{ave}}$ is the average of OYR for each earthquake level. Here, we can find three important facts; first, the RAE has maximum values at a similar Q_y/W if the earthquake loadings are the same. Second, the OYR increases as the earthquakes intensity increases, and finally, the ratio of the increments of OYR becomes decreased for a large earthquake (about 1·02g).

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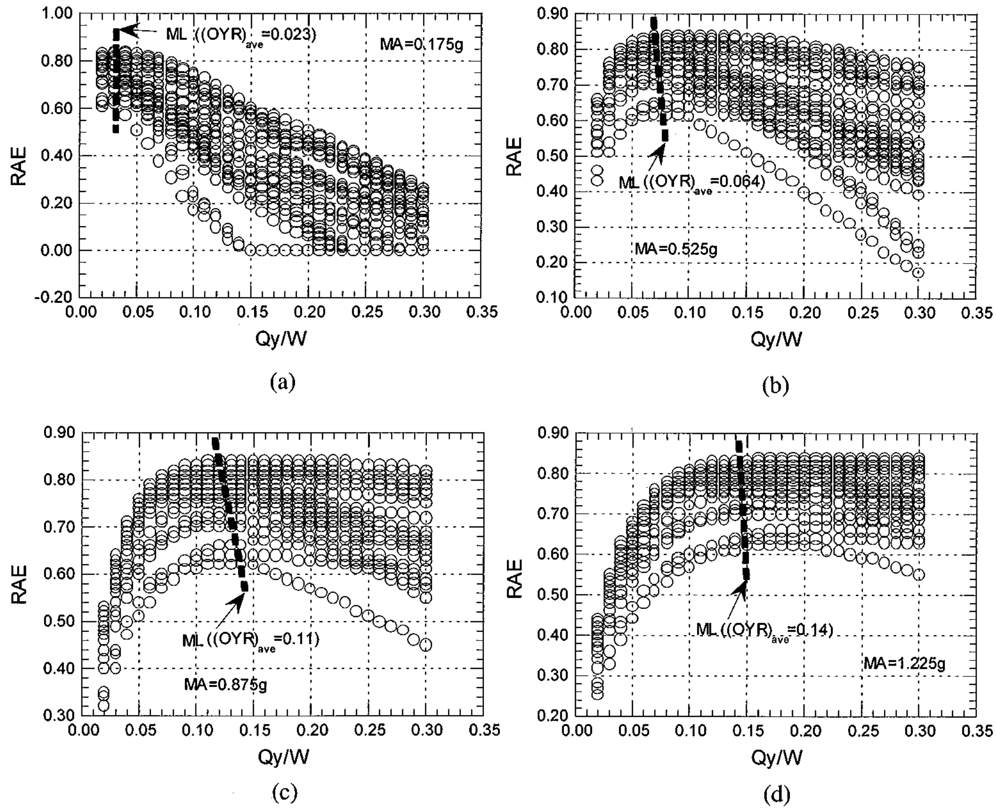

Figure 7. The relationship between RAE and Q_y/W: (a) Q_y/W and RAE under 0·175g; (b) Q_y/W and RAE under 0·525g; (c) Q_y/W and RAE under 0·875g; (d) Q_y/W and RAE under 1·225g;

6. PROPOSED FORMULAS FOR DETERMINING OYR

Figure 8 shows plotting of $(\mathrm{OYR})_{\mathrm{ave}}$ in Table III. Here, $(\mathrm{OYR})_{\mathrm{ave}}$ increases as the earthquake level increases proportionally. But for over 1·05g, the ratio of increments of the $(\mathrm{OYR})_{\mathrm{ave}}$ become decreased.

Thus, two formulas can be introduced by this turning point as shown in equations (6) and (7). Equation (7) is less than 1·05g and equation (7) is equal or greater than 1·05g. EG is the ratio of maximum earthquake acceleration ($u_{g\,\max}$) to gravity acceleration (g). These two equations are obtained from the $(\mathrm{OYR})_{\mathrm{ave}}$ as linear equations.

$$\mathrm{OYR} = 0{\cdot}0011 + 0{\cdot}122\,\mathrm{EG}\ (\mathrm{EG} < 1{\cdot}05) \tag{6}$$

$$\mathrm{OYR} = 0{\cdot}07 + 0{\cdot}057\,\mathrm{EG}\ (\mathrm{EG} \geqslant 1{\cdot}05) \tag{7}$$

7. APPLICATION TO TWO DIFFERENT TYPES OF EARTHQUAKES

The proposed formulas are obtained based on the El Centro type of earthquake loadings. Therefore, it needs to be examined for other types of earthquake loadings. Two kinds of

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Table III. OYR for each earthquake level

TO1	TB1	TB2	0·175g	0·350g	0·525g	0·70g	0·875g	1·05g	1·225g
0·25	0·3	1·5	0·03	0·06	0·09	0·19	0·24	0·29	0·21
0·25	0·3	3·0	0·03	0·05	0·08	0·10	0·13	0·15	0·18
0·25	0·3	4·5	0·03	0·05	0·08	0·10	0·13	0·15	0·17
0·25	0·3	6·0	0·04	0·05	0·07	0·09	0·11	0·14	0·16
0·25	0·6	1·5	0·02	0·07	0·10	0·14	0·17	0·20	0·23
0·25	0·6	3·0	0·02	0·05	0·07	0·09	0·11	0·13	0·15
0·25	0·6	4·5	0·02	0·04	0·05	0·07	0·09	0·10	0·12
0·25	0·6	6·0	0·03	0·04	0·06	0·07	0·09	0·11	0·12
0·25	0·9	1·5	0·02	0·06	0·09	0·12	0·15	0·17	0·20
0·25	0·9	3·0	0·02	0·04	0·06	0·08	0·09	0·11	0·13
0·25	0·9	4·5	0·02	0·04	0·05	0·07	0·08	0·10	0·11
0·25	0·9	6·0	0·03	0·04	0·05	0·07	0·08	0·10	0·11
0·50	0·3	1·5	0·02	0·06	0·09	0·12	0·15	0·18	0·21
0·50	0·3	3·0	0·03	0·04	0·06	0·08	0·10	0·12	0·14
0·50	0·3	4·5	0·02	0·05	0·07	0·10	0·12	0·14	0·17
0·50	0·3	6·0	0·02	0·04	0·06	0·08	0·10	0·12	0·13
0·50	0·6	1·5	0·02	0·05	0·07	0·09	0·11	0·14	0·16
0·50	0·6	3·0	0·02	0·04	0·06	0·08	0·09	0·11	0·13
0·50	0·6	4·5	0·02	0·04	0·06	0·08	0·09	0·11	0·13
0·50	0·6	6·0	0·02	0·04	0·05	0·07	0·08	0·10	0·11
0·50	0·9	1·5	0·03	0·05	0·07	0·09	0·11	0·13	0·15
0·50	0·9	3·0	0·02	0·04	0·06	0·07	0·09	0·11	0·13
0·50	0·9	4·5	0·02	0·04	0·06	0·07	0·09	0·11	0·12
0·50	0·9	6·0	0·02	0·04	0·05	0·07	0·08	0·10	0·12
0·75	0·3	1·5	0·02	0·04	0·06	0·08	0·10	0·12	0·14
0·75	0·3	3·0	0·02	0·04	0·06	0·07	0·09	0·11	0·12
0·75	0·3	4·5	0·02	0·04	0·06	0·08	0·10	0·11	0·13
0·75	0·3	6·0	0·02	0·04	0·05	0·07	0·08	0·10	0·12
0·75	0·6	1·5	0·02	0·04	0·06	0·08	0·10	0·12	0·14
0·75	0·6	3·0	0·02	0·04	0·06	0·07	0·09	0·11	0·13
0·75	0·6	4·5	0·02	0·04	0·05	0·07	0·09	0·10	0·12
0·75	0·6	6·0	0·02	0·04	0·05	0·07	0·08	0·10	0·12
0·75	0·9	1·5	0·03	0·05	0·07	0·09	0·11	0·13	0·15
0·75	0·9	3·0	0·02	0·04	0·06	0·07	0·09	0·11	0·13
0·75	0·9	4·5	0·02	0·04	0·05	0·07	0·09	0·10	0·12
0·75	0·9	6·0	0·02	0·04	0·06	0·08	0·09	0·11	0·13
	$(\mathrm{OYR})_{\mathrm{ave}}$		0·023	0·045	0·064	0·085	0·11	0·13	0·14

earthquake loadings (Taft 1953 and Kobe 1995) are introduced and compared with OYR analysing for each earthquake loading on the condition of the same earthquake level. We may consider Taft as a plate type earthquake and Kobe as direct below type earthquake. Table IV shows the OYR results for two earthquakes. Analysed OYR and OYR by the proposed formulas (6) or (7) have similar values for Taft but analysed OYR is greater than OYR by equations (6) or (7) for Kobe. In case of the direct below type earthquake, the large seismic energy concentrate on a part of earthquake wave and an intensity of destruction is larger than the plate boundary type even if the maximum earthquake acceleration is the same. Therefore, values with about 1·8 times the proposed formula will be recommended for the direct below type earthquake.

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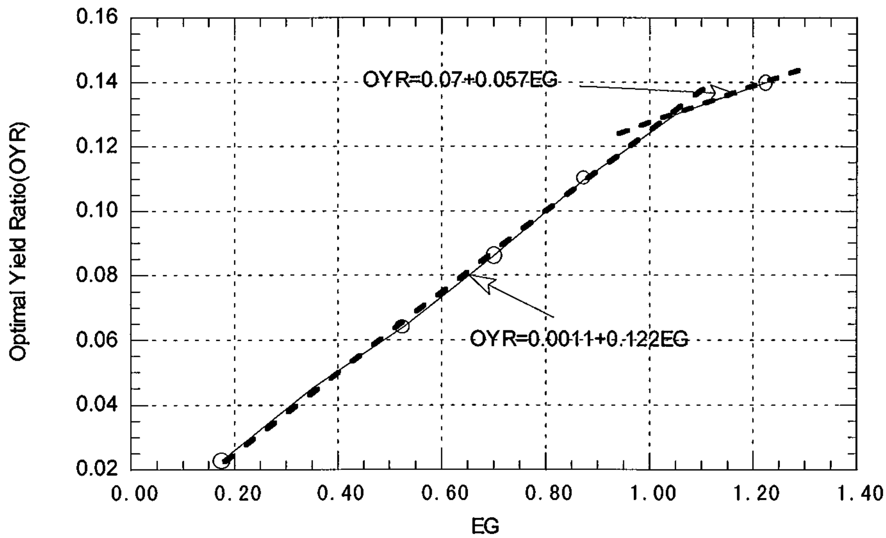

Figure 8. Plotting of $(\mathrm{OYR})_{\mathrm{ave}}$

Table IV. Application to different type earthquakes

Earthquake loading	Maximum acceleration	Analysed OYR	By formula (6) or (7)
Taft 1953	0·18g	0·023	0·025
Kobe 1995	0·83g	0·18	0·10

8. COMPARISON OF PREVIOUS AND THIS RESEARCH

Skinner discussed that the OYR is proportional to the earthquake amplitude based on minimum shear forces. DIS used 0·03, 0·05, 0·07, and 0·10 regardless of earthquake amplitude for Q_d/W. In this study, the OYR is examined for various bilinear models which can represent the regular bridges with the bilinear isolator presently. OYR is obtained based on RAE which can consider various minimum structural responses (shear forces, accelerations and displacements). Here, these three methods for determining OYR are compared for a given isolated bridge model ($T_{O1} =$ 0·25 sec, $T_{b1} = 0{\cdot}30$ sec, $T_{b2} = 6{\cdot}0$ sec, $M_s = 1000$ kg and $M_p = 20$ kg) under two different earthquake levels (0·35g and 1·225g). Table V shows the comparison of the structural responses between the previous and this method. Q_p (N) is the absolute maximum shear force at the piers. The values of OYR in Table V are chosen based on Reference 2 for Skinner's method and Reference 4 for the DIS method. For DIS, Q_d/W is chosen as 0·05 for 0·35g and 0·07 for 1·225g arbitrarily since there is no mention of OYR according to each earthquake level. These Q_d can be onverted using equation (8).

In equation (8), D_y (0·37 cm) is the yield displacement of the isolator and K_{b2} (=65·95 N/cm) is the plastic stiffness of the isolator. D_y and K_{b2} can be obtained from parameters of the given

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Table V. Comparisons of the previous and this method

Item	Skinner		DIS		This study	
MA	0·35g	1·225g	0·35g	1·225g	0·35g	1·225g
OYR	0·050	0·18	0·052	0·052	0·043	0·14
Q_p (N)	945	3300	942	3909	949	3316
AMA (cm/sec^2)	370	1296	371	1228	363	1269
RAE	0·84	0·84	0·84	0·67	0·83	0·83

models. The results of this study shown in Table V is similar to Skinner's method based on minimum lateral forces. In the case of DIS, the force of the piers is larger than the other two results having difference of about 590 N for 1·225g and is similar for 0·35g. The RAE of DIS for 1·225g shows low values compared to the other two methods. The AMA shows similar values for all results but it shows values in this study comparing with the other two methods.

9. DESIGN STRATEGY

A seismic isolation device consists of two components. One is a flexible element to lengthen periods of structures and the other is a stiff element to absorb external seismic energy. In the Lead Rubber Bearing (LRB), the lead core provides the initial stiffness (K_{b1}) and a reliable yield level (Q_d). The initial stiffness of the isolator must resist small load conditions: wind, braking, centrifugal, temperature and small earthquakes elastically. If the external forces reach to the yield force of the isolator (Q_y), the period shift of structures will occur to the plastic range and shear force will be decreased remarkably due to the lengthen periods. After yielding, the energy dissipation will occur. The minimum plan size is governed by the dead load and live load requirements. The thickness of the internal rubber layers is determined by the vertical load, vertical stiffness and rotational capacity requirements. The total rubber thickness in the bearing (hence the number of layers) is generally governed by the thermal loads, and the desired reduction and distribution of earthquake force. The minimum diameter of the lead core is determined by the requirement to maintain small displacements under combinations of wind, braking, centrifugal and thermal load.[4]

Here, we introduce a two-step seismic isolation design concept to realize more reliable and safe designs and to adopt the proposed formulas for determining OYR. Figure 9 shows the relationship between force and displacement for the isolator, pier, and composite model (isolator + pier) to explain the two-step seismic isolation design concept.

In Figure 9, Q_m is the maximum shear force of the isolator, D_p is the elastic displacement of the pier, D_{yc} is the yield displacement of the composite model, D_{mc} is the maximum displacement of the composite model, K_p is the stiffness of the pier, K_B is the effective stiffness of the isolator, K_C is the effective stiffness of the composite model, K_{pb1} is the composite stiffness of the elastic phase, and K_{pb2} is the composite stiffness of the plastic stiffness.

In a bilinear-type seismic isolation design, the design stage can be classified into two stages; one stage is the elastic design stage, and the other stage is the plastic design stage. The elastic design stage includes elastic stiffness, limited elastic design displacement and yield force of the isolator

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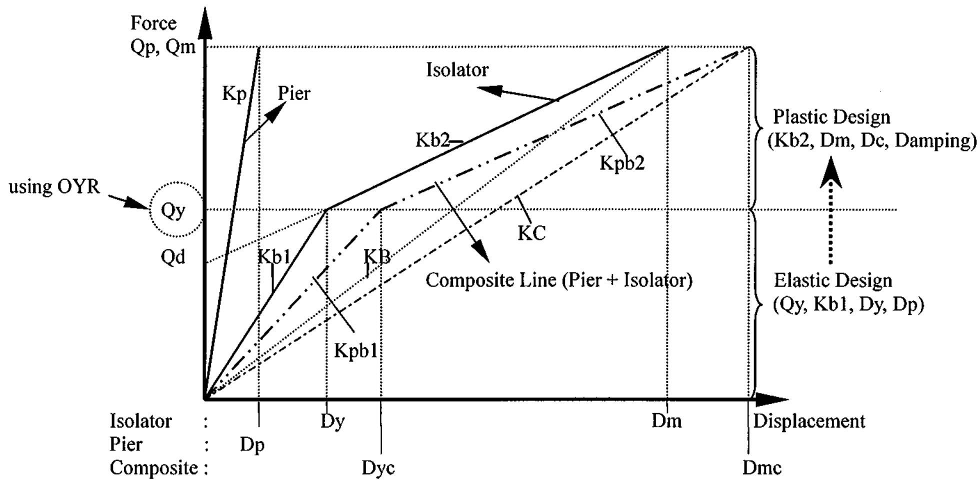

Figure 9. Two-step seismic isolation design concept

under small load conditions. The optimal Q_y/W (OYR) can be adapted in equation (9) in the elastic design stage and OYR must be larger than small load level (braking load etc). As mentioned above, the yield level of isolator must satisfy several conditions; decreasing shear force, limited elastic displacement (high initial stiffness) and large amount of absorbed energy to the input seismic energy as well. OYR obtained from the proposed formulas can assure these requirements. Once the OYR is determined, we do not need to consider the elastic part design. The plastic design stage includes plastic stiffness, design displacement, and damping ratio design under large earthquake loadings. By separated designs (elastic and plastic), more reliable and stable design can be accomplished. This design method can consider characteristics of isolators and flexibility of piers simultaneously. But a further detailed study is necessary to evaluate the damping ratios.

9.1. Elastic design stage

In this design stage, the elastic period Tb1 and optimal yield level of the isolator Q_y are determined under the small load; wind load, braking load, temperature load and small earthquake loadings statically. Here, the OYR can assure the maximum RAE. Equation (9) shows the optimal yield force of isolator and equation (10) shows the composite elastic stiffness of the isolator.

$$Q_y = W\,\mathrm{OYR} \tag{9}$$

$$K_{pb1} = \frac{K_{b1}}{1 + K_{b1}/K_p} \tag{10}$$

K_{pb1} can be determined from a limited displacement of elastic conditions under the service load considering serviceability and stability. These two parameters control the elastic design stage. If the obtained optimal yield force of the isolator, $(Q_y)_{opt}$, is less than the allowable yield force

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limited, $(Q_y)_{allow}$, the $(Q_y)_{allow}$ will be selected as the optimal design yield force. The $(Q_y)_{design}$ must be checked under all possible small load. The D_y can be determined from the elastic allowable displacement.

9.2. Plastic design stage

This design stage is for the large earthquake loadings. An equivalent linearization method must be introduced and the plastic period, evaluation of equivalent damping, equivalent stiffness and design displacement are all determined through trial and error. Equation (11) shows composite stiffness of the plastic phase, ξ_c is the composite damping ratio, T_C is the composite effective period of composite model, and W is the total weight of structures.

$$K_{pb2} = \frac{K_{b2}}{1 + K_{b2}/K_p} \tag{11}$$

$$\xi_c = \frac{2}{\pi}\left(\frac{Q_y/W}{Q_m/W}\right)\left(1 - \frac{T_{pb1}^2}{T_C^2}\right) \tag{12}$$

$$T_C = 2\pi\sqrt{\frac{D_{mc}}{Q_m}\frac{W}{g}} \tag{13}$$

CONCLUSIONS

(1) RAE is a very useful factor to evaluate eathquake resistance.
(2) By the proposed formulas which can determine OYR, the seismic isolation design can be conducted for two phases (elastic and plastic) independently.
(3) An optimal yield force is related to maximum accelerations of earthquake loadings.
(4) An optimal yield force is proportional to earthquake amplitude.
(5) Structural responses have steady values at maximum RAE.
(6) For large earthquakes (about $1{\cdot}05\,g$ over), the change of increments of OYR become decreased.

APPENDIX

Glossary of terms and abbreviations

Two-step Seismic Isolation Design	By using Optimal Yield Ratio (OYR) of seismic devices earthquake resistance will be improved and a seismic isolation design stage can be conducted independently for elastic and plastic design stage.
2-DOF	two-degree-of-freedom
AEI	hysteretic Absorbed Energy by the Isolator
AMA	Absolute Maximum Accelerations
AMD	Absolute Maximum Displacements
AMS	Absolute Maximum Shear forces

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AMSW	the ratio of Absolute Maximum Shear forces to total Weight of structures
DIS	Dynamic Isolation System Inc.
EG	the ratio of maximum Earthquake acceleration to Gravity acceleration
G	Gathered values
LRB	Lead Rubber Bearing
MA	Maximum Acceleration of seismic loading
ML	Maximum Line
OYR	Optimal Yield Ratio
RAE	the Ratio of Absorbed Energy by the isolator to the total input energy
S	Scattered values
TC	composite effective period of composite model
TIE	Total Input Energy

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